OnLine Journal of Biological Sciences

Original Research Paper

The Effect of Differentiated Nitrogen Fertilization using Satellite Navigation Systems on the Spring Wheat (*Triticum aestivum* L.) Crop Yield in the Conditions of Chernozem-Like Soils in the Northern Forest Steppe of the Tyumen Region of Russia

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Article history
Received: 25-08-2022
Revised: 17-11-2022
Accepted: 12-12-2022

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Abstract: Soil cultivation without layers turnover impeded the process of nitrate nitrogen accumulation compared with plowing. The traditional scheme of mineral fertilization applying the averaged standard did not create a heterogeneous level of nutrient supply in primary soil cultivation systems. These factors set them in unequal conditions by default in terms of nitrogen supply to crops. Solid mineral fertilization with the use of precision farming systems in subcompartments, taking into consideration nutrient concentration in soil and the estimated crop yield changes the function of nitrogen status formation. The aim was to study nitrogen status while applying an innovative approach to primary soil cultivation using satellite navigation systems. The experiments were carried out on meadow-chernozem, and nitrogen status was studied in plowing, differentiated, subsurface tillage, and soil cultivation without layers turnover. Nitrate nitrogen was defined by the ionometric method. Moderate supply was registered in plowing and differentiated tillage in the 0-20 cm layer with 10.1-11.8 mg/kg. During the tillering phase, $N\text{-}NO_3$ supply amounted to 16.6-15.2 mg/kg which indicated a high supply of crop plants. On fields with subsurface tillage and no primary soil cultivation, a moderate supply of nitrate nitrogen was observed-10.1-10.8 mg/kg. Innovative technology including differentiated mineral fertilization decreased spatial variability of $N\text{-}NO_3$ supply to 8.2-10.4 mg/kg before spring wheat (*Triticum aestivum* L.) seeding, during tillering phase its variability dropped to 15.3%, having the benefit of accumulation with resource-saving tillage: 11.9-12.7 mg/kg. Optimization of nitrogenous nutrition in the case of differentiated mineral fertilization with precision farming systems application in off-line mode helped achieve the maximum spring wheat yield-3.63-4.03 t/ha in soil cultivation without turning over layers.

Keywords: Primary Soil Cultivation System, Nitrogen Status, Differentiated Fertilization, Mineral Fertilizers Satellite Navigation Systems, Spring Wheat

Introduction

In cultivated plant nutrition systems, nitrogen is often the main agrochemical factor affecting soil fertility (Sun *et al*., 2020). It is a component of simple and conjugated proteins, nucleic acids, part of chlorophyll, phosphatides, alkaloids, and other organic compounds of a plant cell. The level of nitrogen in soil affects crop yield and quality (Baigonussova *et al*., 2021; Saikenova *et al*., 2021; Filippova *et al*., 2022). The main ways to adjust nitrogen levels in the soil are scientifically grounded crop rotation, soil cultivation, and organic and mineral fertilizers (Johnston *et al*., 2009; Beare, 2017; Yang *et al*., 2022).

The primary soil cultivation system in crop rotation is defined as the supply of nitrate nitrogen to crop plants. The choice of deep or subsurface tillage in different edaphic-climatic zones is extremely important since it is connected with soil fertility recovery (Woźniak and Gos, 2014; Suleimenov *et al*., 2016; Bai *et al*., 2021).

An increasing share of chemical energy in the energy balance of intensive farming creates prerequisites for the reduction in mechanical energy input in soil cultivation. It defines global trends of minimizing primary soil cultivation with an increase in chemicals use in agriculture (Popova *et al.*, 2013; Powlson *et al*., 2014; Vasin *et al.*, 2020).

However, when plowing is replaced with subsurface tillage and its depth is reduced, biological activity in soil and mineralization of its organic matter decreases (Perfiliev and Vyushina, 2019; Vlasenko *et al*., 2019; Lomanovskiy and Korchagina, 2021). As a result, soil cultivation without turning over layers is less effective compared to traditional deep tillage in terms of nitrate nitrogen accumulation in the 0-30 cm layer **(**Gilev *et al*., 2012). At the same time, the common scheme of mineral fertilization using the averaged standard by types of primary soil cultivation systems under study creates unequal terms by default in terms of nitrogen supply to plants. The use of precision farming systems in crop growing procedures modifies the function of soil cultivation in the formation of nitrogen status.

Therefore, this study aims to study nitrogen status while applying an innovative approach to primary soil cultivation using satellite navigation systems.

Research objectives featured:

- Track nitrate nitrogen dynamics by types of primary soil cultivation during the spring wheat (*Triticum aestivum* L.) growing period
- Study $N\text{-}NO_3$ supply to cultivated plants in case of differentiated nitrogen fertilization in off-line mode
- Provide agroeconomic assessment of nitrogen status formation using an innovative approach to primary soil cultivation

Materials and Methods

The article analyses experimental material collected in chernozem-like soils in the northern forest-steppe of the Tyumen Region. Tests to research different systems of primary soil cultivation have been conducted since 1977. The research paper examines the results over the period of 1978-1983 when the traditional (classic) approach to carrying out experiments prevailed. This method provides for the application of mineral fertilizers at an average rate for the planned yield according to the experimental variants. Starting from 2008, this experiment has been adjusted thanks to improved technical capacities. Using the satellite navigation system, mineral differentiated fertilization was applied in offline mode by variants and replications. Therefore, to understand agrochemical processes, periods were taken to compare the application of mineral fertilizers using the traditional method (1978-1983), the initial period of applying the differentiated method (2009-2011), and the final period of long-term use of innovative technologies for the cultivation of spring wheat (2019-2020).

The test area where comprehensive research was carried out is located on the territory of a scientific-experimental farm at Northern Trans-Ural State Agricultural University. The farm is situated in the in-between rivers area of the Tura-Pyshminskoye region (coordinates-N 57° 9' 26.64" E 65° 21' 32.832"), on a plain with a slight tilt towards the south-west, on a plowed land in 7 kilometers from the flood plain terrace of the Tura River steep coast and 1.5 kilometers from Utyoshevo village (Fig. 1). According to natural zoning, the scientific-experimental farm is in the northern forest-steppe subzone. The forest-steppe zone landscape is characterized by slightly undulating plains with saucer-shaped hollows. Parallel rather narrow and long, quite low sloping hills (low ridge) are alternated with wide shallows (hollows) which somehow disturbs the plain-like landscape.

The test field has meadow-chernozem, solodic, shallow, heavy loamy soil. Thanks to its chemical content this soil has high natural fertility. Humus level in the 0-30 cm layer is 7.96%, and active acidity is 6.9%. The level of labile phosphorus and exchangeable potassium in the topsoil is increased and very high.

Weather conditions in 2019 were favorable for growing spring wheat (*Triticum aestivum* L.). The sum of active temperatures was 2180°C, the amount of precipitation over the growing season was 324 mm, Hydrothermal Coefficient (HTC) was 1.49. The year 2020 was less favorable as with the sum of active temperatures being 2463°C and 226 mm of precipitation, HTC was 0.92 (Fig. 2).

To provide equal conditions for nitrogen supply to spring wheat in the studied types of primary soil cultivation, differentiated fertilization was used.

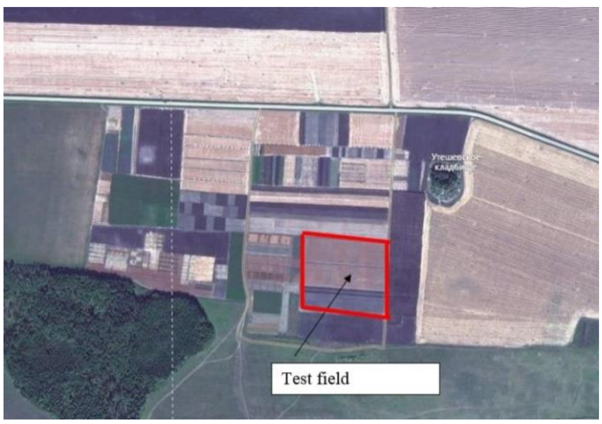

Fig. 1: Map of the test area

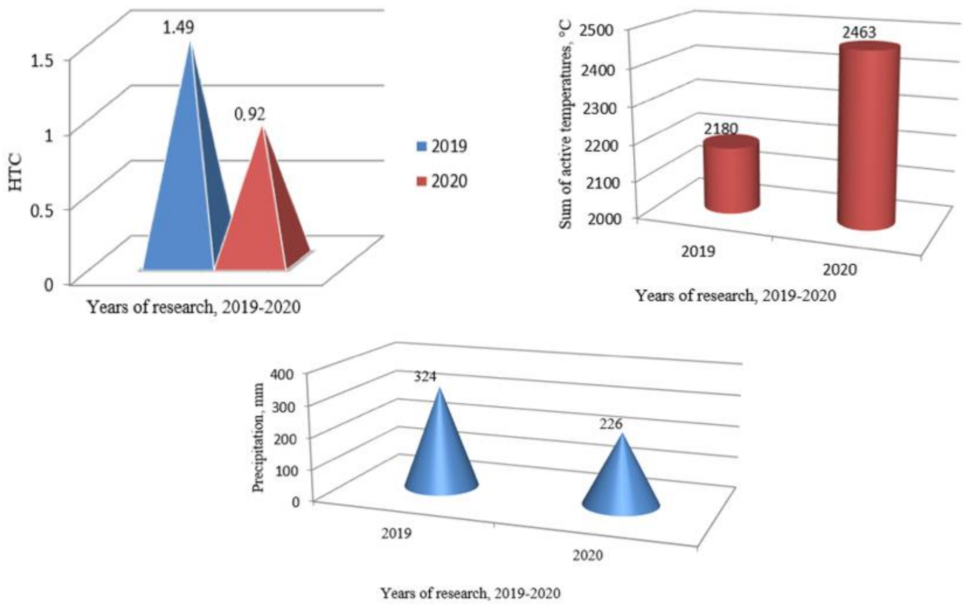

Fig. 2: Weather condition indicators (HTC, sum of active temperatures, precipitation data), years of research 2019-2020

Before differentiated nitrogen fertilization taking into consideration nutrient concentration in soil and the estimated spring wheat crop yield, the test field was digitalized by driving around the field on a vehicle with navigation equipment (Agronavigator board navigation complex, Agrobusiness consulting company, Russia) fine-tuned by GLONASS/GPS satellite signals. A topological map of variants with replications (sub-compartment) linked to geographic coordinates was developed using Google Earth software. Soil sampling points were registered with Garmin GPS MAP 62S manual navigator (USA).

After the chemical analysis of the soil, the calculation of the fertilizer required amount was done by sub-compartments. The results were exported to the built-in navigation computer installed on a tractor and linked to a linear actuator for differentiated fertilization during seeding with SKP-2.1 seeder in autonomous mode. When the seeder starts moving, the navigation signals detector transmits a signal specifying the location of the seeder on the field to the built-in computer that features an electronic map of mineral fertilization assignment. Having processed the information, the Built-in Navigation Computer (BNC) sends a signal upon entrance to the next sub-compartment (replication) where the norm of mineral fertilizers may be different from the previous sub-compartment. The BNC control unit transmits the task to open (close) the seed roller to the reducing unit lever (linear actuator). The level of nitrate nitrogen was identified by ionometric method before seeding, during the tillering phase-stem elongation, and before spring wheat harvest in the 0-10, 10-20, and 20-30 cm layers. The method is based on the extraction of nitrates by a solution of potassium alum with a mass concentration of 1%, with a ratio of a soil sample to solution volume of 1:2.5, and subsequent measurement of nitrates in the extract through an ion-selectic electrode.

Spring wheat was harvested by direct combining using SAMPO 500 (Sampo-Rosenlew company, Finland)-with three replications and converted to 100% purity and 14% humidity. The financial viability of soil cultivation and mineral nutrition level was estimated based on profit, grain cost, and production profitability:

$$Cost\ price = Costs\ for 1 ha / crop\ yield, doll./t$$

$$Profitability = Net\ income / costs * 100, \%$$

Nitrogen status was studied in types of primary soil cultivation systems of grain crop rotation with seeded fallow:

1. Deep tillage (control)
2. Differentiated: Deep tillage for annual grass at 28-30 cm, shallow for spring wheat at 10-12 cm
3. Subsurface: Subsoiling (45 cm) with PTchN-2,3 chisel plow for annual grass and shallow tillage (10-12 cm) for spring wheat on the 2nd and 3rd field
4. Without primary soil cultivation (direct seeding)

Field expert *V* 1.3 Pro Software package shows statistical processing statistical processing of field test data in crop research using B. Dospekhov methodology. We used the method of determining the smallest significant difference between the results of the studied variants. Using the analysis of variance, the sum of squared deviations for the studied factors and their interaction was calculated together with HCP_{05} to assess the significance of individual differences, and the contribution of factors in the total variability of characteristics (Grebennikova, 2015).

Results

Annual deep tillage and differentiated tillage (with deep tillage for annual grasses and subsurface tillage for spring wheat and barley) for grain seeding before nitrogen fertilization facilitated the increase in N-NO_3 in the 0-40 cm layer up to 7.9-8.8 mg/kg of soil. It was also aligned with a low level of nitrate nitrogen content (Table 1).

However, these primary soil cultivation systems ensured its accumulation in the 0-20 cm layer up to 10.1 and 11.8 mg/kg-the moderate supply level.

One of the main sources of nitrogen replenishment for plants is mineral fertilization. Ammonium nitrate embedding with a 60 kg/ha application rate before seeding spring wheat helped increase nitrogen in the nitrate form by the tillering phase-stem elongation reaching the level of high supply with 16.6-15.2 mg/kg of soil for deep and differentiated primary soil cultivation systems. The benefit of these cultivation types in terms of N-NO_3 content was also registered in the 0-40 cm layer-11.8 and 11.5 mg/kg of soil. An increase in nitrate nitrogen level after mineral fertilization was observed on a field where subsurface tillage was used and with no primary cultivation in the 0-20 cm layer only reaching the moderate supply level-10.1-10.8 and low supply-in the 0-40 cm layer 7.2-7.9 mg/kg. At the same time, spatial variability of N-NO_3 in the 0-30 cm layer of meadow-chernozem soil before fertilization amounted to 59.4%, while in the spring wheat tillering phase-to 47.9%.

Therefore, deep and differentiated primary soil cultivation developed a more favorable nitrogen status for cultivated plants compared to subsurface or zero tillage. It also resulted in spring wheat level decreasing by 0.3 and 0.95 t/ha with absolute values being 3.45 and 2.82 t/ha. For plowing and differentiated tillage (deep tillage for annual grasses and two-year subsurface tillage for grain), spring wheat crop yield was the same-3.77 and 3.78 t/ha. Calculations have shown that for the studied primary soil cultivation systems, the strength of the relationship between spring wheat crop yield and nitrate nitrogen supply in the topsoil was average (0.472). According to the coefficient of determination, nitrate nitrogen during tillering phase-stem elongation defined spring wheat crop yield by 22.3%. The shift to innovative technologies of spring wheat cultivation using satellite navigation systems changed the functional role of primary cultivation when developing agrochemical indicators of soil fertility. The identified pattern of nitrate nitrogen accumulation in the soil cultivation systems under research was observed in the early years of precision farming (2009-2011) and after its long-term use (2019-2020). Therefore, the results of nitrogen status research were combined for these years.

Differentiated nitrogen fertilization considering nitrate nitrogen content and the estimated crop yield by types of primary soil cultivation systems under study facilitated the decrease of spatial variability of N-NO_3 already at the stage of spring wheat seeding (Table 2). Fluctuations in nitrate nitrogen supply before mineral fertilization by the tested types amounted to 23.2%.

Differentiated application of ammonium nitrate using satellite navigation in an off-line mode made it possible to level spatial variability of N-NO_3 for the primary soil cultivation systems under study relatively before fertilization (37.5%) by 14.3% with its absolute content in the 0-30 cm layer being 8.2-10.4 mg/kg.

During spring wheat growth and development, two mutually exclusive processes take place in soil-accumulation of nitrate nitrogen due to nitrification and its absorption by crop plants. Spatial variability of nitrate nitrogen supply during the tillering phase-stem elongation continued dropping to 15.3-by 22.2% compared to the period before fertilization. At the same time, there is a consistent pattern of increasing nitrogen supply in the nitrate form by types of soil cultivation without turning over layers.

The innovative technology of mineral fertilization using satellite navigation helped achieve even formation of nitrogen status in different types of primary soil cultivation systems. Moderate supply of nitrogen in the soil in case of soil cultivation without turning over layers enhanced synthesis of organic and nitrogenous matter.

During an important phase for spring wheat-initiation of the ear, differentiated application of ammonium nitrate helped all the studied types of primary soil cultivation reach the moderate level of N-NO_3 supply-10.2-12.7 mg/kg. By the time of spring wheat harvesting, nitrate nitrogen was at 5.8-7.3 mg/kg with spatial variability being 23.4%.

The identified consistent pattern in precision farming makes it possible to conduct a functional reassessment of primary soil cultivation systems with minimization elements. As has been mentioned above, the process of nitrogen status development was preserved by research periods. Thus, to assess different systems of primary soil cultivation, the economic parameters of the periods were combined and averaged. At the same time, the accumulative effect of differentiated fertilization has been observed. If in 2009-2022, variability of N-NO_3 before spring wheat seeding amounted to 20.3% and in 2019-2020-to 24.8%, in the tillering phase variability remained in 2009-2011 at the level of 26.1% and in 2019-2022 it reduced to 17.0%. It should also be noted that this technology reduces spatial variability of the content of nitrogen in the nitrate form, however, it does not drastically solve the problem of variability. Before the spring wheat harvest, variability increased to 30.9-29.8% approaching the original level of 37.5%.

Spring wheat crop yield in case of subsurface tillage at 10-12 cm depth over the research years on average was 3.63 t/ha and exceeded crop in case of plowing by 0.07 t/ha while the profitability of grain production by 7.4% (Table 3).

Table 1: Nitrate nitrogen in the soil, mg/kg depending on primary soil cultivation system (average for the period of 1978-1983)

	Before fertilization in layer			During the spring wheat tillering phase after fertilization with an N_{60} application rate		
Primary soil cultivation system	0-20	20-40	0-40	0-20	20-40	0-40
Deep	10.1	5.7	7.9	16.6	6.9	11.8
Differentiated	11.8	5.8	8.8	15.2	7.7	11.5
Subsurface	8.0	4.1	6.1	10.8	5.0	7.9
No primary cultivation	6.3	3.0	4.7	10.1	4.2	7.2
HCP_{05}, mg/kg	1.8	1.2	1.5	2.3	1.7	1.9
Spatial variability of N-NO_3 in the 0-30 cm layer, %			59.4			47.9

Table 2: Nitrate nitrogen supply (mg/kg of soil) in the 0-30cm layer depending on primary soil cultivation in case of differentiated mineral fertilization

	Time of soil sampling								
	Before seeding			Tillering-stem			Before harvesting		
Soil cultivation system	2009-2011	2019-2020	Average	2009-2011	2019-2020	Average	2009-2011	2019-2020	Average
Deep (control)	8.4	11.7	10.1	9.7	10.7	10.2	7.8	4.1	6.0
Differentiated: Deep tillage for annual grass at 28-30 cm, shallow for spring wheat at 10-12 cm	6.9	9.5	8.2	12.0	11.8	11.9	6.6	5.0	5.8
Subsurface: Chisel plow for peas and oat -45 cm; shallow for wheat-10-12 cm	8.7	12.0	10.4	11.6	12.1	11.9	9.0	5.5	7.3
No primary cultivation	7.9	10.2	9.1	12.7	12.7	12.7	9.1	4.1	6.6
HCP_{05}, mg/kg			1.2			1.4			1.0
Spatial variability of N-NO_3 in the 0-30 cm layer, %	20.3	24.8	23.2	26.1	17.0	15.3	30.9	29.8	23.4

Table 3: Financial viability of spring wheat cultivation in different primary soil cultivation systems with differentiated mineral fertilization (average for the period of 2009-2011 and 2019-2020)

	Crop yield, t/ha					
Primary soil cultivation system	2009-2011	2019-2020	Average	Direct costs, doll./t	Cost price, doll./t	Profitability, %
Deep (control)	3.96	3.21	3.56	350.4	98.4	34.6
Differentiated: Deep tillage for annual grass at 28-30 cm, shallow for spring wheat at 10-12 cm	3.71	3.62	3.63	338.6	93.3	42.0
Subsurface: Chisel plow for peas and oat at 45 cm; shallow for 2 years for wheat at 10-12 cm	3.96	3.89	4.02	334.1	83.1	59.4
No primary soil cultivation	4.19	3.55	4.03	335.3	83.2	59.2
HCP_{05}, mg/kg			0.28			

Optimization of nitrogenous nutrition in case of differentiated mineral fertilization with subsurface shallow tillage with chisel plowing at 45 cm depth for annual grasses for haylage and without primary soil cultivation helped achieve the maximum spring wheat yield-4.02-4.03 t/ha. Weather conditions differed throughout research periods, however, a clear pattern of increasing spring wheat yield in the case of tillage without turning over layers with 0.34-0.68 t/ha compared to tillage in 2019-2020 can be observed. For an unbiased assessment of primary soil cultivation effectiveness, calculations for all the research years were made in the prices valid in 2020.

It is worth mentioning that in the cost structure of these primary soil cultivation systems, nitrogen fertilizers occupied up to 10% with their cost being higher by 0.24-6.68 doll./ha compared to deep tillage.

Costs for primary soil cultivation, at the same time, decreased compared with plowing by 16.5-21.6 doll./ha.

Despite increased costs for nitrogen fertilizers, differentiated fertilization using satellite navigation systems, and reduced costs for soil cultivation without turning over layers, spring wheat yield was more profitable than in the case of deep tillage-42.0-59.4%.

Discussion

Numerous research results (Vlasenko *et al*., 2019; Tian *et al*., 2020; Gu *et al*., 2022) indicate the benefits of deep tillage for nitrification processes. According to Uvarov and Karabutov (2012), plowing increased nitrate nitrogen content in the soil while subsurface tillage impedes the supply of nitrogen to crop plants.

When conducting earlier tests, the primary soil cultivation system without turning over layers decreased the mobilization processes of nitrate nitrogen from soil organic matter (Abramov, 2022). Lower microflora activity resulted in poorer accumulation of nitrate nitrogen in the 0-40 cm layer up to 4.7-6.1 mg/kg for these types of primary soil cultivation before mineral fertilization.

Differentiated fertilization provided equal conditions for the types of primary soil cultivation under study. In our research, the use of satellite navigation systems for mineral fertilization considering nitrogen content in soil and estimated spring wheat crop yield made it possible to develop a favorable soil nitrogen status for cultivated plants. Spatial variability of nitrate nitrogen supply during the tillering phase dropped to 15.3 by 22.2% compared to the period before fertilization. There is a consistent pattern of increasing nitrogen supply in the nitrate form by types of soil cultivation without turning over layers, which compares well with the figures of (Eryomin and Kibuk, 2017; Hati *et al*., 2021; Maliarchuk *et al*., 2021). The conclusions of the studies previously carried out by Eryomin and Kibuk (2017), and Abramov and Sherstobitov (2018) showed that differentiated application of fertilizers on the planned yield in the "off-line" mode reduced and supported throughout the growing season the uniformity of the field on the content of nitrate nitrogen, decreased the coefficient of spatial heterogeneity.

The use of precision farming systems in crop growing modifies the function of soil cultivation in the formation of nitrogen status.

The use of satellite navigation systems in precision farming should hold a special place in the digitalization of plant cultivation production processes. The studied way of differentiated nitrogen fertilization with resource-saving primary tillage can be used in similar soil and climatic conditions in Western Siberia.

Conclusion

Natural processes of nitrate nitrogen accumulation in the case of subsurface and zero tillage were less intensive than in the case of deep and differentiated tillage. The traditional way of mineral fertilization using the averaged standard could not solve the problem of monogamic nitrogen nutrients in primary soil cultivation systems under study. Differentiated mineral fertilization taking into consideration nitrate nitrogen content by types of primary soil cultivation decreased its spatial variability before spring wheat seeding by 14.3% compared to the period before fertilization. This pattern was observed during the tillering phase, having, however, the benefit of accumulation with resource-saving tillage: 11.9-12.7 mg/kg.

Optimization of mineral nutrition in the case of differentiated nitrogen fertilization using satellite navigation systems made it possible to have the biggest spring wheat crop yield of 3.63-4.03 t/ha in the studied types of soil cultivation without turning over layers. The grain received here had a low cost price of 83.1-93.3 doll./t and higher profitability of its production-42.0-59.4% compared to deep tillage. Today, remote sensing of pests, diseases, and weeds, and provision of nutrition elements to plants using artificial satellites, and unmanned drones are studied that will allow shifting to differentiated chemicalization in precise farming.

Acknowledgment

The authors thank the reviewers for their contribution to the peer evaluation of this study.

Funding Information

The authors have not received any financial support or funding to report.

Author's Contributions

All authors equally contributed to this study.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues are involved.

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